Claims

[c1] 1. A method for limiting stress levels in an aircraft-powering turbofan assembly by controlling unstable movement of laminar-to-turbulent boundary layer transition on fan blades of the turbofan assembly during aircraft flight, said method comprising:

including on a flying aircraft, an aircraft-powering turbofan assembly comprising multiple fan blades mounted on a fan disc and each of said fan blades having a leading edge, a trailing edge, and two side surfaces that comprise a high-pressure side surface and a low-pressure side surface, said turbofan assembly being configured such that a laminar-to-turbulent boundary layer transition occurs on at least one of said side surfaces of each of said fan blades during flight; and wherein a plurality of said fan blades are each adapted to further comprise a laminar-to-turbulent boundary layer transition control feature at the side surface of the respective fan blade at which the transition occurs, each of said control features initiating and positionally stabilizing a laminar-to-turbulent boundary layer transition to a location upon the respective fan blade between said control feature and the respective fan blade's trailing edge so that an aggregate limited stress occurring in the turbofan assembly at a mounting of the respective fan blade to the fan disc is substantially maintained below fifty megapascals during flight within the aircraft's operating envelope.

[c2] 2. A method for limiting stress levels in an aircraft-powering turbofan assembly by controlling unstable movement of laminar-to-turbulent boundary layer transition on fan blades of the turbofan assembly during aircraft flight, said method comprising:

including on a flying aircraft, an aircraft-powering turbofan assembly

comprising multiple fan blades mounted on a fan disc and each of said fan blades having a leading edge, a trailing edge, and two side surfaces that comprise a high-pressure side surface and a low-pressure side surface, said turbofan assembly being configured such that a laminar-to-turbulent boundary layer transition occurs on at least one of said side surfaces of each of said fan blades during flight; and wherein a plurality of said fan blades are each adapted to further comprise a laminar-to-turbulent boundary layer transition control feature at the side surface of the respective fan blade at which the transition occurs, each of said control features initiating and positionally stabilizing a laminar-to-turbulent boundary layer transition to a location upon the respective fan blade between said control feature and the respective fan blade's trailing edge so that an aggregate limited stress occurring in the turbofan assembly at a mounting of the respective fan blade to the fan disc is substantially maintained below twenty megapascals during flight within the aircraft's operating envelope.

[c3] 3. A method for limiting stress levels in an aircraft-powering turbofan assembly by controlling unstable movement of laminar-to-turbulent boundary layer transition on fan blades of the turbofan assembly during aircraft flight, said method comprising:

including on a flying aircraft, an aircraft-powering turbofan assembly comprising multiple fan blades mounted on a fan disc and each of said fan blades having a leading edge, a trailing edge, and two side surfaces that comprise a high-pressure side surface and a low-pressure side surface, said turbofan assembly being configured such that a laminar-to-turbulent boundary layer transition occurs on at least one of said side surfaces of each of said fan blades during flight; and wherein a plurality of

said fan blades are each adapted to further comprise a laminar-to-turbulent boundary layer transition control feature at the side surface of the respective fan blade at which the transition occurs, each of said control features initiating and positionally stabilizing a laminar-to-turbulent boundary layer transition to a location upon the respective fan blade between said control feature and the respective fan blade's trailing edge so that an aggregate limited stress occurring in the turbofan assembly at a mounting of the respective fan blade to the fan disc is substantially maintained below ten megapascals during flight within the aircraft's operating envelope.

[c4] 4. The method as recited in any one of claims 1-3, wherein said aggregate limited stress measured in the mounting of the respective fan blade to the fan disc is composed at least partially by fluctuating stresses.

[c5] 5. The method as recited in claim 4, wherein said fluctuating stresses are at least partially caused by an unsteady aerodynamic force associated with an oscillatory chordwise translation of said boundary layer transition point along the chord of the respective fan blade.

[c6] 6. The method as recited in any one of claims 1-3, further comprising: utilizing said laminar-to-turbulent boundary layer transition control feature in response to detecting structural degradation in a similarly configured turbofan assembly without the control feature.

[c7] 7. The method as recited in any one of claims 1-3, further comprising: utilizing a strain gauge to assess the aggregate stress level experienced in the turbofan assembly proximate the mounting of the respective fan blade to the fan disc during flight.

[c8] 8. The method as recited in any one of claims 1-3, wherein said blades

are operating under non-stall conditions.

[c9] 9. The method as recited in any one of claims 1-3, wherein the flight envelope of said aircraft ranges from zero to seventy thousand feet pressure altitude and the fan blades are in stall-free operation.

[c10] 10. The method as recited in any one of claims 1-3, further comprising: enabling a reduction in flight-time based inspection intervals of the turbofan assembly.

[c11] 11. The method as recited in any one of claims 1-3, further comprising: enabling a reduction in flight-time based inspection intervals of constituent components of the turbofan assembly.

[c12] 12. The method as recited in claim 11, wherein said fan blades are constituent components of the turbofan assembly.

[c13] 13. The method as recited in claim 11; wherein said fan disc is a constituent component of the turbofan assembly.

[c14] 14. The method as recited in any one of claims 1-3, further comprising: obtaining the approval of regulatory bodies for reduced frequency, flight-time based inspection intervals because of limited stress levels enabled by the utilization of the laminar-to-turbulent boundary layer transition control feature.

[c15] 15. The method as recited in any one of claims 1-3, further comprising: maintaining a specific fuel consumption when said laminar-to-turbulent boundary layer transition control feature is included that is substantially equal to the specific fuel consumption of a similarly configured turbofan assembly without said control feature.

[c16] 16. The method as recited in any one of claims 1-3, further comprising: communicating said limited stress levels in product promotions.

[c17] 17. The method as recited in any one of claims 1-3, further comprising: communicating said limited stress levels for purposes of at least one of flight envelope expansion, product differentiation and sales promotion.

[c18] 18. A method for limiting undesirably high stress levels in an aircraft-powering turbofan assembly that would otherwise result from unstable movement of laminar-to-turbulent boundary layer transition on fan blades of the turbofan assembly during aircraft flight and the promotion of said stress limitation as a product sales feature, said method comprising: including on a flying aircraft, an aircraft-powering turbofan assembly comprising multiple fan blades mounted on a fan disc and each of said fan blades having a leading edge, a trailing edge, and two side surfaces that comprise a high-pressure side surface and a low-pressure side surface, said turbofan assembly being configured such that a laminar-to-turbulent boundary layer transition occurs on at least one of said side surfaces of each of said fan blades during flight; and wherein a plurality of said fan blades are each adapted to further comprise a laminar-to-turbulent boundary layer transition control feature at the side surface of the respective fan blade at which the transition occurs, each of said control features initiating and positionally stabilizing a laminar-to-turbulent boundary layer transition to a location upon the respective fan blade between said control feature and the respective fan blade's trailing edge and thereby limiting stresses induced by an instability in the location of the laminar-to-turbulent boundary layer transition by a factor of at least one-half in comparison to similar, but untreated fan blade configurations; and

communicating said limited stress levels for purposes of flight envelope expansion, product differentiation and sales promotion.

[c19] 19. A turbofan fan blade adapted to fix transition of an unstable laminar boundary layer transition to a turbulent boundary layer at a side surface of the blade during operation as a component in a turbofan fan assembly, said fan blade comprising:

a leading edge, a trailing edge, and two side surfaces comprising a high-pressure side surface and a low-pressure side surface; and

at least one of said two side surfaces having an essentially smooth surface portion located between said leading and trailing edges, said essentially smooth surface portion being interrupted by a surface deviation, said surface deviation being configured to fix transition of a positionally unstable laminar boundary layer transition to a turbulent boundary layer at a location between said surface deviation and said trailing edge during operation of said fan blade in said turbofan fan assembly thereby controlling fatigue inducing, structurally damaging unsteady aerodynamic forces experienced upon at least one of the blades and a fan disc during operation.

[c20] 20. A turbofan fan blade adapted to fix transition of an unstable laminar boundary layer transition to a turbulent boundary layer at a side surface of the blade during operation as a component in a turbofan assembly, said fan blade comprising:

a leading edge, a trailing edge, and two side surfaces comprising a high-pressure side surface and a low-pressure side surface; and

a feature to suppress flow unsteadiness and subsequent structural resonance on a turbofan fan blade by inducing transition of a positionally unstable laminar boundary layer transition to a turbulent boundary layer

at a location between said feature and said trailing edge during operation of said fan blade in said turbofan assembly thereby controlling fatigue inducing, structurally damaging unsteady aerodynamic forces experienced upon at least one of the blades and a fan disc during operation.

[c21] 21. A turbofan fan blade assembly comprising:

fan blades, each having a leading edge, a trailing edge, and two side surfaces that comprise a high-pressure side surface and a low-pressure side surface; and

each of a plurality of said fan blades comprising a feature to suppress flow unsteadiness and subsequent structural resonance on said fan blade by inducing transition of a positionally unstable laminar boundary layer transition to a turbulent boundary layer at a location between said feature and said trailing edge of said fan blade during operation of said turbofan fan blade assembly thereby controlling fatigue inducing, structurally damaging unsteady aerodynamic forces experienced upon at least one of said fan blades and a fan disc during operation.

[c22] 22. A turbofan engine comprising:

an inlet, an outlet and a fan blade assembly installed therein at a position between said inlet and said outlet;

said fan blade assembly including turbofan fan blades mounted on a fan disc and configured for rotational operation within said turbofan engine, each of said fan blades having a leading edge, a trailing edge, and two side surfaces that comprise a high-pressure side surface and a low-pressure side surface; and

each of a plurality of said turbofan fan blades comprising a feature to fix transition of a positionally unstable laminar boundary layer transition to a

turbulent boundary layer at a location between said feature and said trailing edge of the blade during operation of said turbofan fan blade assembly thereby controlling fatigue inducing, structurally damaging unsteady aerodynamic forces experienced upon at least one of said turbofan fan blades and a fan disc during operation.

[c23] 23. A turbofan-powered aircraft comprising:

at least one turbofan based power unit, mounted to an aircraft fuselage and/or wing, and comprising an inlet, an outlet and a fan blade assembly installed therein at a position between said inlet and said outlet;

said fan blade assembly includes multiple turbofan fan blades mounted on a fan disc and configured for rotational operation within said turbofan body, each of said turbofan fan blades having a leading edge, a trailing edge, and two side surfaces that comprise a high-pressure side surface and a low-pressure side surface; and

each of a plurality of said turbofan fan blades comprising a feature to suppress flow unsteadiness and subsequent structural resonance on said respective turbofan fan blade by inducing transition of a positionally unstable laminar boundary layer transition to a turbulent boundary layer at a location between said feature and said trailing edge of said respective turbofan fan blade during flight-operation of said aircraft thereby controlling fatigue inducing, structurally damaging unsteady aerodynamic forces experienced upon at least one of said respective turbofan fan blades and said fan disc during flight-operation.

[c24] 24. A turbofan fan blade adapted to fix transition of an unstable laminar boundary layer transition to a turbulent boundary layer at a side surface of the blade during operation as a component in a turbofan fan assembly, said fan blade being produced by a method comprising:

obtaining a turbofan fan blade having a leading edge, a trailing edge, and two side surfaces consisting of a high-pressure side surface and a low-pressure side surface; and

providing a feature to suppress flow unsteadiness and subsequent structural resonance on a turbofan fan blade by inducing transition of a positionally unstable laminar boundary layer transition to a turbulent boundary layer at a location between said feature and said trailing edge during operation of said fan blade in said turbofan fan assembly thereby controlling fatigue inducing, structurally damaging unsteady aerodynamic forces experienced upon said turbofan fan blade.

[c25] 25. A turbofan fan blade adapted to reattach a separated boundary layer thereby controlling an unsteady aerodynamic load at a side surface of the blade during operation as a component in a turbofan fan assembly, said fan blade being produced by a method comprising:

obtaining a turbofan fan blade having a leading edge, a trailing edge, and two side surfaces comprising a high-pressure side surface and a low-pressure side surface; and

providing a feature on said turbofan fan blade that reattaches a separated boundary layer to said fan blade thereby controlling fatigue inducing, structurally damaging unsteady aerodynamic forces experienced upon said turbofan fan blade.

[c26] 26. The invention as recited in claim 25, wherein said separated boundary layer reattachment device is at least one of (1) a vortex generator and (2) a turbulator and (3) a transition strip in the form of a raised elevation above the smooth surface of said fan blade and (4) a transition strip in the form of a recessed elevation below the smooth surface of said fan blade.

[c27] 27. A method for providing a turbofan fan blade configured to transition an unsteady laminar boundary layer to a turbulent boundary layer at a side surface of the blade during operation as a component in a turbofan fan assembly, said fan blade having a leading edge, a trailing edge, and two side surfaces consisting of a high-pressure side surface and a low-pressure side surface, said method comprising:
providing a feature to suppress flow unsteadiness and subsequent structural resonance on said turbofan fan blade by inducing transition of a positionally unstable laminar boundary layer transition to a turbulent boundary layer at a location between said feature and said trailing edge during operation of said fan blade in said turbofan fan assembly thereby controlling fatigue inducing, structurally damaging unsteady aerodynamic forces experienced upon the blade during operation.

[c28] 28. A method for providing a turbofan fan blade configured to reattach a separated boundary layer to a side surface of the blade during operation as a component in a turbofan fan assembly, said fan blade having a leading edge, a trailing edge, and two side surfaces consisting of a high-pressure side surface and a low-pressure side surface, said method comprising:
providing a feature on said turbofan fan blade that reattaches a separated boundary layer to said fan blade thereby controlling fatigue inducing, structurally damaging unsteady aerodynamic forces experienced upon at least one of the blades and fan disc during operation.

[c29] 29. The invention as recited in claim 28, wherein said separated boundary layer reattachment feature is at least one of (1) a vortex generator and (2) a turbulator and (3) a transition strip in the form of a raised elevation above the smooth surface of said fan blade and (4) a

transition strip in the form of a recessed elevation below the smooth surface of said fan blade.

[c30] 30. A method for retrofitting an earlier manufactured turbofan fan blade with an adaptation configured to transition an unstable laminar boundary layer transition to a turbulent boundary layer at a side surface of the fan blade during operation as a component in a turbofan fan assembly, said method comprising:

obtaining an earlier manufactured fan blade having a leading edge, a trailing edge, and two side surfaces comprising a high-pressure side surface and a low-pressure side surface; and

providing a feature on said fan blade that transitions a positionally unstable laminar boundary layer transition to a turbulent boundary layer at a location between said feature and said trailing edge during operation of said fan blade in a turbofan fan assembly thereby controlling fatigue inducing, structurally damaging unsteady aerodynamic forces in said fan blade.

[c31] 31. A method for producing a turbofan fan blade configured to transition an unstable laminar boundary layer transition to a turbulent boundary layer at a side surface of said fan blade during operation as a component in a turbofan fan assembly, said method comprising adapting a fan blade having a leading edge, a trailing edge, and two side surfaces consisting of a high-pressure side surface and a low-pressure side surface with a feature on at least one of said side surfaces, said feature configured to fix transition of a positionally unstable laminar boundary layer transition to a turbulent boundary layer at a location between said feature and said trailing edge during operation of said fan blade in a turbofan fan assembly thereby controlling fatigue inducing, structurally damaging unsteady

aerodynamic forces in said turbofan fan blade.

[c32] 32. An arrangement including a feature to suppress flow unsteadiness and subsequent structural resonance on a fan blade in a turbofan based power unit installed on an aircraft and thereby maintaining operationally induced fan blade and/or fan disc stress levels within a range to minimize structural degradation of said fan blade and/or fan disc, said arrangement comprising:

a rotating fan blade assembly including multiple fan blades, mounted on a fan disc, and each of said fan blades having a leading edge, a trailing edge, and two side surfaces that comprise a high-pressure side surface and a low-pressure side surface; said aircraft operating under conditions that cause at least laminar and turbulent boundary layers to form on at least one of the side surfaces of the blade with a boundary layer transition between; and

a plurality of said turbofan fan blades each comprising a boundary layer control feature at the side surface which transitions a positionally unstable laminar boundary layer transition to a turbulent boundary layer at a location between said feature and said trailing edge of the respective blade during flight or ground operation of the turbine fan blade assembly and thereby maintaining operationally induced stress levels measured on at least one of said fan blades and said fan disc within a range to minimize structural degradation.

[c33] 33. The invention as recited in claim 32, further comprising:

enabling a reduction in flight-time based inspection intervals of the fan blades and related fan disc of said power unit.

[c34] 34. The invention as recited in claim 32, further comprising:

enabling solicitation of regulatory bodies for approved reduction of flight-

time based inspection intervals with the feature incorporated on the power unit.

[c35] 35. The invention as recited in claim 32, wherein said range of operationally induced stress levels to minimize structural degradation of said fan blade and/or fan disc is fifty MPa, and less.

[c36] 36. The invention as recited in claim 32, wherein said range of operationally induced stress levels to minimize structural degradation of said fan blade and/or fan disc is twenty MPa, and less.

[c37] 37. The invention as recited in claim 32, wherein said range of operationally induced stress levels to minimize structural degradation of said fan blade and/or fan disc is ten MPa, and less.

[c38] 38. The invention as recited in claim 32, with said feature, maintaining a specific fuel consumption substantially equal to that of a substantially identically configured power unit without said feature.

[c39] 39. The method as recited in any one of claims 1-3, wherein said laminar-to-turbulent boundary layer transition control feature is located on at least one of said two side surfaces having an essentially smooth surface portion located between said leading and trailing edges and said feature being characterized by a surface deviation constituting a departure from said essentially smooth surface portion.

[c40] 40. The method as recited in claim 39, wherein said departure from said essentially smooth surface portion is constituted by a reduced-elevation surficial portion, compared to said essentially smooth surface portion.

[c41] 41. The method as recited in claim 39, wherein said departure from said essentially smooth surface portion is constituted by a raised-elevation

surficial portion, compared to said essentially smooth surface portion.

[c42] 42. The method as recited in claim 41, wherein said raised-elevation surficial portion is provided by applying an adhesive to at least one of said two side surfaces, the thickness of said adhesive constituting the thickness of said raised-elevation surficial portion.

[c43] 43. The method as recited in claim 41, wherein said raised-elevation surficial portion is provided by applying grit fixed to at least one of said two side surfaces using an adhesive, said grit establishing peak elevations of said raised-elevation surficial portion.

[c44] 44. The method as recited in claim 41, wherein said raised-elevation surficial portion is formed by at least one of bonding, mechanical, electrical, thermodynamic and chemical based techniques upon at least one of said two side surfaces.

[c45] 45. The method as recited in claim 39, wherein said departure from said essentially smooth surface portion is greater than three inches long and is positioned chordwise between said fan blade leading edge and said fan blade trailing edge.

[c46] 46. The method as recited in claim 39, wherein said departure from said essentially smooth surface portion is an elongate strip-shaped area of raised elevation having a length of three or less inches and positioned chordwise between said fan blade leading edge and said fan blade trailing edge.

[c47] 47. The method as recited in claim 39, wherein said departure from said essentially smooth surface portion is an elongate strip-shaped area of raised elevation having a width of less than one-half inch.

[c48] 48. The method as recited in claim 39, wherein said departure from said essentially smooth surface portion is an elongate strip-shaped area of raised elevation having a width of less than two-tenths of an inch.

[c49] 49. The method as recited in claim 39, wherein said departure from said essentially smooth surface portion is an elongate strip-shaped area of raised elevation having a width of approximately one-tenth of an inch.

[c50] 50. The method as recited in claim 39, wherein said departure from said essentially smooth surface portion is an elongate strip-shaped area of raised elevation having a tip-end distanced approximately one-half inch from a tip of the respective turbofan blade.

[c51] 51. The method as recited in claim 39, wherein said departure from said essentially smooth surface portion is an elongate strip-shaped area of raised elevation having a tip-end distanced at least one-half inch from a tip of the respective turbofan blade.

[c52] 52. The method as recited in claim 39, wherein said departure from said essentially smooth surface portion is an elongate strip-shaped area of raised elevation positioned behind said leading edge and forward of the laminar to turbulent boundary layer transition point on the untreated fan blade.

[c53] 53. A method for modifying an existing turbofan assembly having a plurality of unmodified fan blades mounted on a fan disc, each of said plurality of unmodified fan blades having a leading edge, a trailing edge, a first side and a second side, the method comprising the steps of: determining a range of translation of an unstable transition point between a laminar and a turbulent boundary layer on at least one of the first side and the second side of at least one of said plurality of unmodified fan

blades, the range of translation of the unstable transition point having a foremost position closest to the leading edge; and

modifying the existing turbofan assembly by positioning a boundary layer transition point stabilizing element on at least one of the first side and the second side of at least one of said plurality of unmodified fan blades between the leading edge and the foremost position of the unstable transition point, thereby

reducing the range of translation of the unstable transition point between the laminar and the turbulent boundary layer by initializing transition from a laminar to turbulent boundary layer upstream of the determined range of translation and thereby minimizing the range of translation of said initiated transition boundary point during use of the modified turbofan assembly; and

reducing aggregate stresses occurring at a mounting of at least one of said plurality of modified fan blades to the fan disc in the modified turbofan assembly to below a predetermined threshold during use of the modified turbofan assembly.

[c54] 54. The method as recited in claim 53, wherein the predetermined threshold is fifty megapascals during use of the turbo fan assembly.

[c55] 55. The method as recited in claim 53, wherein the predetermined threshold is twenty megapascals during use of the turbo fan assembly.

[c56] 56. The method as recited in claim 53, wherein the predetermined threshold is ten megapascals during use of the turbo fan assembly.

[c57] 57. The method as recited in claim 53, wherein the unstable translation of said laminar to turbulent boundary layer transition point includes an oscillatory chordwise translation on at least one of said plurality of

unmodified fan blades.

[c58] 58. The method as recited in claim 53, further comprising the step of enabling a reduction in frequency of flight-time based inspections of the existing turbofan assembly.

[c59] 59. The method as recited in claim 53, further comprising the step of expanding a flight envelope of the modified turbofan assembly.

[c60] 60. The method as recited in claim 53, wherein said transition stabilizing element is at least one of (1) a vortex generator and (2) a turbulator and (3) a transition strip in the form of a raised elevation above a smooth surface of each of said plurality of fan blades and (4) a transition strip in the form of a recessed elevation below a smooth surface of each of said plurality of fan blades.

[c61] 61. The method as recited in claim 60, wherein said raised elevation is provided by applying an adhesive to at least one of the first side and the second side, a thickness of said adhesive constituting the thickness of said raised-elevation.

[c62] 62. The method as recited in claim 60, wherein said raised elevation is provided by applying grit to at least one of the first side and the second side using an adhesive, said grit establishing peak elevations of said raised-elevation.

[c63] 63. The method as recited in claim 60, wherein said raised and/or recessed elevations are created by at least one of bonding, spraying, forming, or the use of any mechanical, electrical, thermodynamic and/or chemical based procedure used to develop said raised or recessed elevations upon at least one of the two side surfaces.

[c64] 64. The method as recited in claim 60, wherein said raised elevation and said recessed elevation include an elongate strip-shaped area having a length of greater than three inches.

[c65] 65. The method as recited in claim 60, wherein said raised elevation and said recessed elevation include an elongate strip-shaped area having a length of three inches or less.

[c66] 66. The method as recited in claim 60, wherein said raised elevation and said recessed elevation include an elongate strip-shaped area having a width of less than one-half inch.

[c67] 67. The method as recited in claim 60, wherein said raised elevation and said recessed elevation include an elongate strip-shaped area having a width of less than two-tenths of an inch.

[c68] 68. The method as recited in claim 60, wherein said raised elevation and said recessed elevation include an elongate strip-shaped area having a width of approximately one-tenth of an inch.

[c69] 69. The method as recited in claim 60, wherein said raised elevation and said recessed elevation include an elongate strip-shaped area having a tip-end distanced approximately one-half inch or less from a tip of each of said plurality of fan blades.

[c70] 70. The method as recited in claim 60, wherein said raised elevation and said recessed elevation include an elongate strip-shaped area having a tip-end distanced at least one-half inch from a tip of each of said plurality of fan blades.